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Toward on-demand modulation and annihilation of aeroelastic limit cycle oscillations with dynamic upstream disturbance generator

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Abstract

Periodic upstream flow disturbances from a bluff body have recently been shown to be able to modulate and annihilate limit cycle oscillations (LCOs) in a downstream aeroelastic wing section under certain conditions. To further investigate these phenomena, we have implemented a controllable wind tunnel disturbance generator to enable quantification of the parameter ranges under which these nonlinear interactions can occur. This disturbance generator, consisting of a pitch-actuated cylinder with an attached splitter plate, can be oscillated to produce a von Karman type wake with vortex shedding frequency equal to the oscillation frequency over a range of frequencies around the natural shedding frequency of the cylinder alone. At vortex shedding frequencies away from the LCO frequency of the wing, forced oscillations were observed in the wing, but the wing did not enter self-sustaining LCOs. However, when disturbances were introduced near the LCO frequency, the initially static downstream wing entered self-sustaining oscillations in the presence of the incoming vortices, and these LCOs persisted when the disturbance generator was stopped. Annihilation of the wing LCOs was also observed disturbance vortices were introduced upstream of the wing in LCO.

Keywords: nonlinear aeroelasticity, limit cycle oscillations, limit cycle control, annihilation, vortices

1 Introduction

The complexity of aeroelastic systems has been studied extensively since the earliest days of aviation. However, the majority of previous work has involved studying the aeroelastic structures themselves. Mitigation and control of flutter phenomenon and nonlinear limit cycle oscillations (LCOs), has largely been explored through structural and aerodynamic modifications. Some examples of this include the use of wing-mounted control surfaces [1, 2], dynamic alteration of wings depending on their operating states [3, 4], or other attachments to wings such as nonlinear energy sinks [5]. While these methods are effective, there is considerably less work which focuses on the impact of flow disturbances such as impinging vortices on aeroelastic stability and LCO phenomena.

Work performed at North Carolina State University (NCSU) in recent years has sought to explore this realm of using upstream flow disturbances to modify the behavior of aeroelastic structures experiencing LCOs. The first study in this line of work examined the interactions between two inline aeroelastic wings [6]. Kirschmeier and Bryant found that the aeroelastic response of the downstream wing was largely dependent on flow disturbances produced by the upstream wing. Specifically, the oscillation frequency of the downstream wing, even in non-LCO situations, was dependent on the LCO frequency of the upstream wing, which acted as an external forcing function on the downstream wing. Additionally, when both wings were exhibiting LCO behavior, the frequency and phase of the downstream wing would “lock-in” to a consistent relationship with the upstream wing.

Following the conclusions from this study, namely the “lock-in” behavior of the downstream wing in a vortex wake, Gianikos et al [7] and Kirschmeier et al [8] devised a setup to examine the response of a downstream wing in a more consistent and well-defined vortex wake. Their apparatus, shown in Figure 1, consisted of a rectangular bluff body with a length-to-width ratio of 2-to-1 placed at varying locations upstream of an aeroelastic wing section with spring-supported pitch and heave degrees of freedom. The wing section was of aspect ratio four and included endplates to produce nominally two-dimensional flow. For upstream flow conditions in the chord-based Reynolds number range of 70,000 to 120,000, a series of experiments were performed in the NCSU Subsonic Wind Tunnel to observe the response of the downstream wing. In these experiments, LCOs were manually triggered in the downstream wing by releasing it from a nonzero pitch deflection and the wing response categorized through real-time measurement of pitch angle and heave displacement. Simultaneously, the time histories of vortices shed from the bluff body were characterized using a load cell, which measured the forces and moments imparted on the bluff body as vortices were shed.

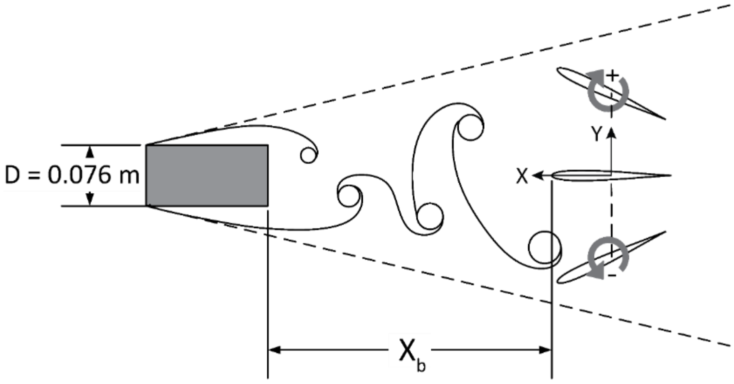

Figure 1: Top view of bluff body and downstream wing apparatus of Gianikos et al. [7]

Results from these experiments, shown in Figure 2a, showed significant modulation in the amplitude of the LCOs experienced by the downstream wing as the bluff body vortex shedding frequency approached a value of three times that of the wing LCO frequency. When the same system was tested with greater pitch-heave coupling, complete annihilation of wing LCOs occurred when the ratio of bluff body vortex shedding frequency approached three times the wing LCO frequency shown in Figure 2b. The concept of LCO modulation and annihilation is not limited to the work done at NCSU, as a considerable reduction in LCO displacement was found in a flat-plate airfoil exposed to incoming gusts produced by a rotating slotted cylinder during a study by Dowell et al [9].

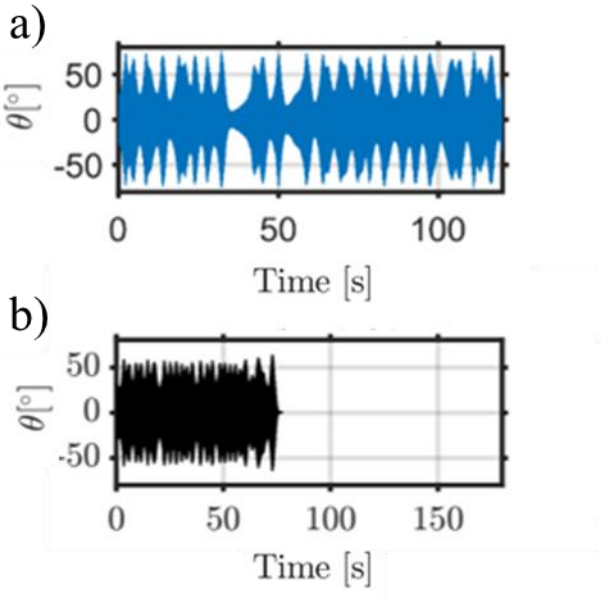

Figure 2: a) Downstream wing pitch amplitude showing LCO modulation. [7] b) Downstream wing pitch amplitude showing LCO annihilation. [8]

While these results reveal that upstream flow disturbances can modify and even suppress LCO in a completely passive and uncontrolled system, being able to produce these phenomena on-demand with a controllable system would enable investigation into the underlying parameter ranges, structural and flow state relationships, and energy exchanges that give rise to these effects. To accomplish this, it was hypothesized that the frequency and phase of vortices impinging on the downstream wing could be controlled using a dynamic, upstream, bluff body. Cylindrical bluff bodies were initially chosen as the focus of future bluff body designs due to the well-studied nature of their wake behavior [10]. However, collaborating researchers at the Air Force Research Laboratory (AFRL) showed that while a static cylinder's shedding frequency is tied to physical properties such as the freestream velocity and cylinder diameter, a prescribed oscillations about the primary axis could alter the shedding frequency and phase [10]. Additionally, the inclusion of a splitter plate attached to the trailing edge of the rotating cylinder could further improve the wake characteristics of the bluff body and produce a well-behaved, von Kármán, vortex street with a shedding frequency equal to the oscillation frequency of the bluff body [10].

In conjunction with researchers at AFRL, Chatterjee et al. [11] determined that a cylinder with attached splitter plate produced the desired wake region when the Strouhal ratio (the ratio of the oscillation frequency, and thereby the forced vortex shedding frequency, to the natural shedding frequency of a cylinder with no splitter plate) fell between 0.8 and 1.4. Additionally, Rockwood and Medina [10] found that a "locked-in" wake could be produced with Strouhal ratios ranging from 0.3 to 1.1.

Following this line of work done at NCSU, the desire to achieve on-demand LCO modulation and annihilation led to the design of a new bluff body disturbance generator. This design focused on producing vortices with variable phase, frequency, and amplitude while not being dependent on freestream velocity. Using this new disturbance generator, a series of experiments to demonstrate on-demand LCO modulation and annihilation was performed in the NCSU Subsonic Wind Tunnel.

2 Methodology

The initial design point for the new bluff body disturbance generator was based on the $f_{shed}/f_{LCO} \rightarrow 3$ operating point in previous experiments wherein LCO modulation and annihilation were observed. Coupled with this information, the Strouhal ratio range discussed by Chatterjee et al. [11] and the Reynolds number range used in previous work were used to create a design space within which the new disturbance generator could be designed. Table 1 shows a range of cylinder diameters which were considered for the design based on these factors.

Table 1: Bluff Body Design Space

St/St_n	$f_{osc}\ (Hz)$	$u_\infty (m/s)$	$D\ (cm)$
0.8	12	8	10.67
0.9	12	8	12.00
1.0	12	8	13.33
1.1	12	8	14.67
1.2	12	8	16.00
1.3	12	8	17.33
1.4	12	8	18.67

From this range of possible values, a cylinder diameter of $D = 10.67$ cm was initially chosen. However, due to construction constraints based on available materials, a final value of $D = 10.48$ cm was implemented, as shown in Figure 3. The disturbance generator oscillation was driven by a SureServo SVL-210b from AutomationDirect (Cumming, GA, USA) and controlled using a Copley Controls (Canton, MA, USA) Xenus XTL-230-18 digital servo drive. A sinusoidal analog input with prescribed amplitude and frequency was fed into the Xenus controller, which then used an internal control loop to ensure correct motion of the disturbance generator.

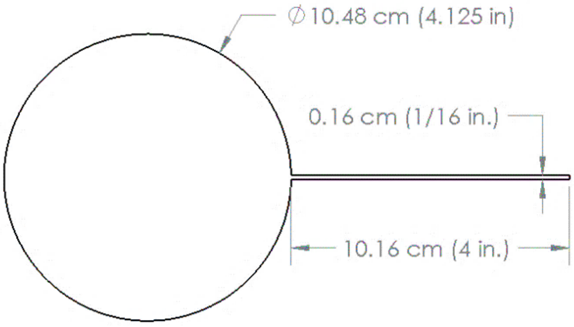

Figure 3: Cross section of bluff body design.

Following initial implementation and validation of the new bluff body disturbance generator, a series of experiments were run to attempt LCO modulation and annihilation with the downstream aeroelastic wing apparatus described by Kirschmeier et al [8]. This series of tests were run in the NCSU Subsonic Wind Tunnel at a constant freestream velocity (u_{∞}), bluff body oscillation amplitude (A_{osc}), and downstream location of the aeroelastic wing measured from cylindrical bluff body center to the wind quarter-chord (x_w) while sweeping across a range of bluff body oscillation frequencies (f_{osc}), as shown in Table 2. While previous work examined cases wherein the bluff body vortex shedding frequency was approximately three times the wing LCO frequency, this preliminary experiment focused on shedding frequencies near the wing LCO frequency.

Table 2: Test Cases

$f_{osc}\ (Hz)$	$\mathrm{A_{osc}}$ (°)	$u_{\infty}(m/s)$	x_w
3.5	30	9.25	8D
3.6	30	9.25	8D
3.7	30	9.25	8D
3.8	30	9.25	8D
3.9	30	9.25	8D
4.0	30	9.25	8D
4.1	30	9.25	8D
4.2	30	9.25	8D
4.3	30	9.25	8D
4.4	30	9.25	8D
4.5	30	9.25	8D

During these tests, a National Instruments PXi with LabVIEW was used to record real-time data at a sampling frequency of $f_s = 500\ Hz$. US Digital (Vancouver, WA, USA) E6-10000 optical encoders were used to record pitch amplitude for both the oscillating disturbance generator and the downstream wing, and a Renishaw LM10 (West Dundee, IL, USA) magnetic linear encoder was used to record heave data for the downstream wing.

3 Results and Discussion

Data gathered during testing was post-processed using MATLAB 2020a. Although this initial round of testing focused on a lower shedding frequency compared to previous work, the new disturbance generator was able to excite LCOs in the downstream wing without the need for a manual trigger, as in previous work. For all cases except the $f_{osc} = 4.0\ Hz$ case, vortices produced by the disturbance generator appeared to act as an external forcing function on the wing, but did not excite LCOs, as shown in Figure 4. Note that the wing pitch and heave oscillations quickly die down when the bluff body oscillations are stopped at $t \approx 125\ s$.

For the case when $f_{osc} = 4.0\ Hz$, which corresponds to $f_{osc} \approx f_{LCO}$, the downstream wing was excited to LCO. Initially the pitch amplitude of the wing showed cyclic growth and decay of oscillation amplitude, as shown in Figure 5, similar to data reported by Gianikos et al [7]. If the disturbance generator oscillation was stopped as the wing pitch amplitude reached its peak ($\approx 50°$), the wing would remain in LCO without the influence of incoming vortices as shown in Figure 6a.

Additionally, during initially maintained LCOs by the downstream wing, activation of the disturbance generator oscillation led to annihilation of the LCOs. The effect was not immediate but was marked by a gradual decline in the amplitude of the wing pitch angle. As the amplitude approached zero, the disturbance generator oscillations were stopped, and the wing came to rest with no noticeable oscillations, as shown in Figure 6b.

Upon further examination, it is likely that the true natural LCO frequency of the downstream wing at this freestream velocity is not $f_{LCO} = 4.0\ Hz$, but rather a value which falls very close to this. The cyclic growth and decay of the wing pitch angle in the presence of incoming vortices at $4\ Hz$ appears to demonstrate a "beat-like" phenomenon, similar to the interference between two signals with slightly differing frequencies. A slight difference in frequency would also explain why the LCO decay in Figure 6b does not begin immediately when the disturbance generator is activated – the delay may be due to the time required for the wing motion and the disturbance vortices to move into the required phase for annihilation to occur. Similarly, in the previous study by Kirschmeier et al. [8], annihilation was observed with $\frac{f_{LCO}}{f_{osc}} = 2.92$. These small deviations from integer frequency ratios may be important to produce LCO annihilation in an open-loop system without control of the wake phase relative to the wing motion.

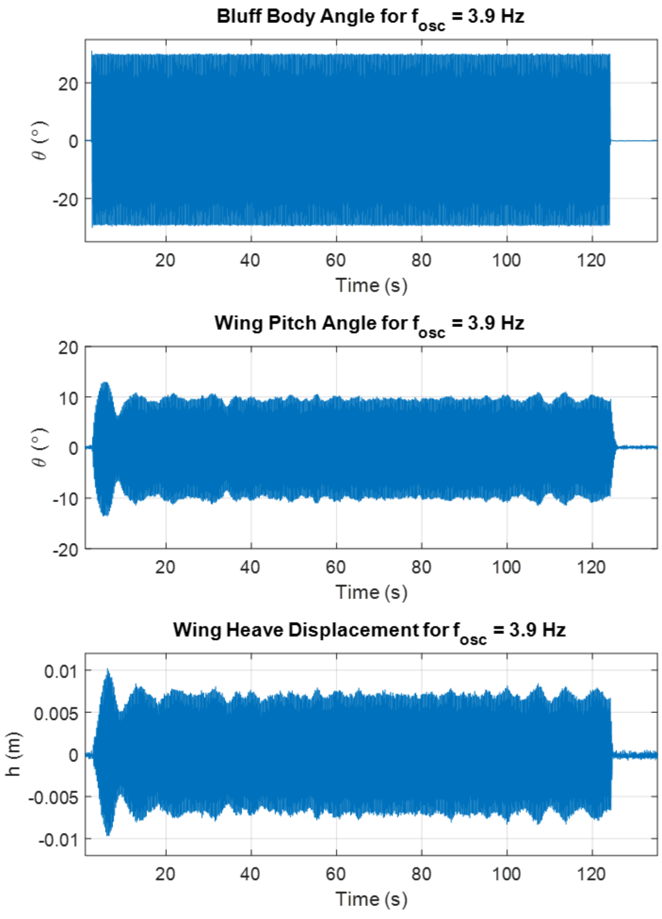

Figure 4: Bluff body angle and wing motion during forced oscillations.

4 Conclusions

The work presented in this paper demonstrates the ability of an upstream disturbance generator, consisting of an oscillation cylinder with attached splitter plate, to modulate, excite, and annihilate LCOs in a downstream aeroelastic wing. Oscillations of the disturbance generator at a rate nearing the natural LCO frequency of the wing produced increasingly large amplitudes in the downstream wing which were used to force the wing into LCOs, while the same interference from incoming vortices when the wing was already undergoing LCOs resulted in annihilation of the LCO amplitude. Additionally, disturbance generator oscillations at other frequencies did not produce the same result in the downstream wing. This work builds on existing studies which demonstrated LCO modulation and annihilation using a static bluff body which produced vortices at a rate tied to the freestream velocity, while the apparatus used in this study is able to produce vortices at a rate which is independent of the freestream velocity. This new apparatus will enable further investigation into the kinematic and aerodynamic states and energy transfer behaviors leading to LCO growth, modulation, and annihilation in response to upstream disturbances. Understanding these phenomena may lead to novel methods of controlling aeroelastic structures in aviation, energy harvesting, and infrastructure applications.

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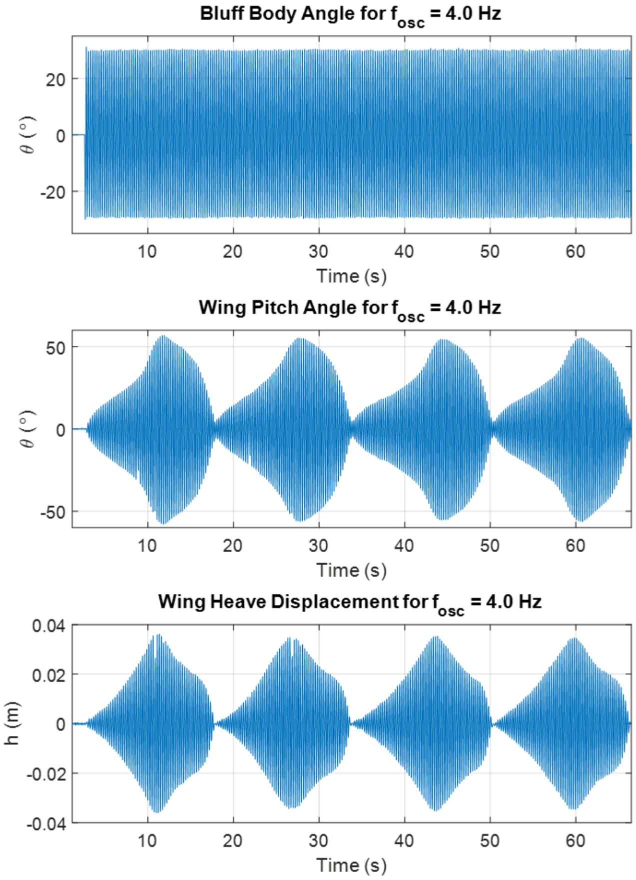

Figure 5: Bluff body and wing motion showing “beat-like” phenomenon at 4.0 Hz.

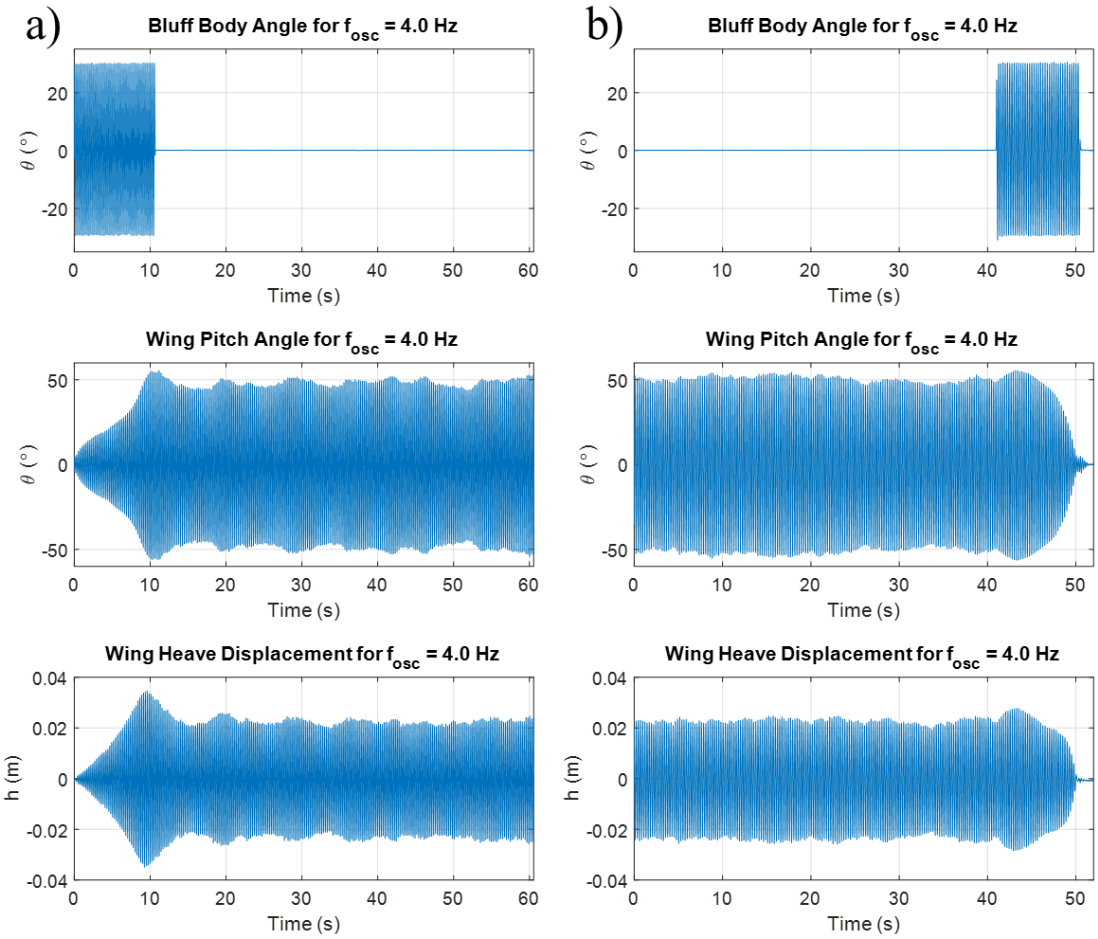

Figure 6: Bluff body and wing motion showing: a) excitation of LCOs and b) annihilation of LCOs.

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